



Indian Journal of Engineering & Materials Sciences
Vol. 27, June 2020, pp. 631-642



Study on dry-sliding wear (DSW) of uncoated IN800 super alloy and sol-gel based dip coated IN800 substrate

Dipak Kumar^{a*} & Kailash Narayan Pandey^b

^aMechanical Engineering Department, Raj Kumar Goel Institute of Technology, Ghaziabad 201003, Lucknow, India

^bMechanical Engineering Department, Motilal Nehru National Institute of Technology Allahabad, Allahabad 211004, India

Received: 10 March 2017 ; Accepted: 28 August 2019

In the present paper, sliding wear characteristics of seven weight% yttria stabilized zirconia (7YSZ) sol-gel deposited on to air plasma sprayed CoNiCrAlY bond-coated Inconel 800 superalloy has been studied. For this, sliding wear tests have performed on pin-on-disc friction and wear test rig by varying experimental parameters applied load, sliding velocity, disc speed and temperature as per L_{16} orthogonal arrays of Taguchi. Taguchi method has been used to perform experiments to know the effect of interaction of variables on dry sliding wear behavior. The optimal experimental parameters have been obtained by orthogonal arrays, signal-to-noise ratio (SNR) and analysis of variance (ANOVA) for uncoated and coated Inconel 800 superalloy substrate. Results have shown temperature as the most influencing parameter for uncoated samples and coated samples, both. However, compared with coated samples, applied load has been found significant factor for uncoated samples. It has been exhibited better wear resistance in the sol-gel derived YSZ coated surface of IN800 superalloy substrate.

Keywords: Dry-sliding wear, Sol-gel thermal barrier coating, IN800 superalloy, Taguchi method

1 Introduction

Superalloys are extensively used as a base material under harsh environment due to their unique mechanical, tribological and high temperature properties¹⁻⁴. Hence, wear characteristics of superalloys are extensively studied⁵⁻⁹.

To further increase the applicability of superalloys at increased temperature, solid particle erosion and sliding wear environment, thermal barrier coatings (TBCs) are applied on the surface of the components. Study of tribological characteristics of the TBCs on superalloy was the subject matter of interest in recent years¹⁰⁻¹⁹. The basic purpose was to provide tribological system possessing low wear rates (WR) and low friction coefficients over a wide range of temperature by making ceramic based coating on the base metal^{17-18, 20}.

In the present study, seven weight% yttria stabilized zirconia (7YSZ) sol-gel thermal barrier coating (TBC) was fabricated on CoNiCrAlY bond-coated Inconel 800 (IN800) superalloy and sliding wear resistance against tungsten carbide disc¹⁵ was determined. The wear tests as per ASTM standard G 99-95a²¹ were conducted on Pin-On-Disc Friction and Wear test rig by varying different parameters such as temperatures

(25-400 °C), disc speed (200- 800 rpm), applied load (15-60N) and sliding velocity (0.5-0.8 m/sec) using L_{16} orthogonal array of Taguchi design of experiment²². The wear behavior of the uncoated Inconel 800 superalloy was also studied for comparison with coated samples. From the Taguchi based experimentation an optimal sliding wear parameter were determined for minimum sliding wear rate (SWR).

2 Experimentation

2.1 Preparation of Samples for Sliding Wear Rate of Uncoated IN800 Substrate (SW-B1)

A cylindrical pin of IN800 superalloy with diameter and length equal to 10 mm and 30 mm respectively, was selected as the specimen for sliding wear test. Flat surfaces of the cylindrical pins of IN800 superalloy were grounded using SiC emery paper numbers 220 to 2000. After grinding of uncoated samples, it was lapped to get the surface finish in the range of R_a 0.023-0.029 μm . Then, each sample was washed into acetone²³. Finally, cleaned samples were dried and weighed using an electronic balance (Make: CONTECH, 224D) having a resolution of 0.01 mg¹⁵. Figure 1 (a & b) shows the as-received and polished uncoated samples before wear test. These samples will be called SW-B1.

*Corresponding author (E-mail: dipakmnit@gmail.com)

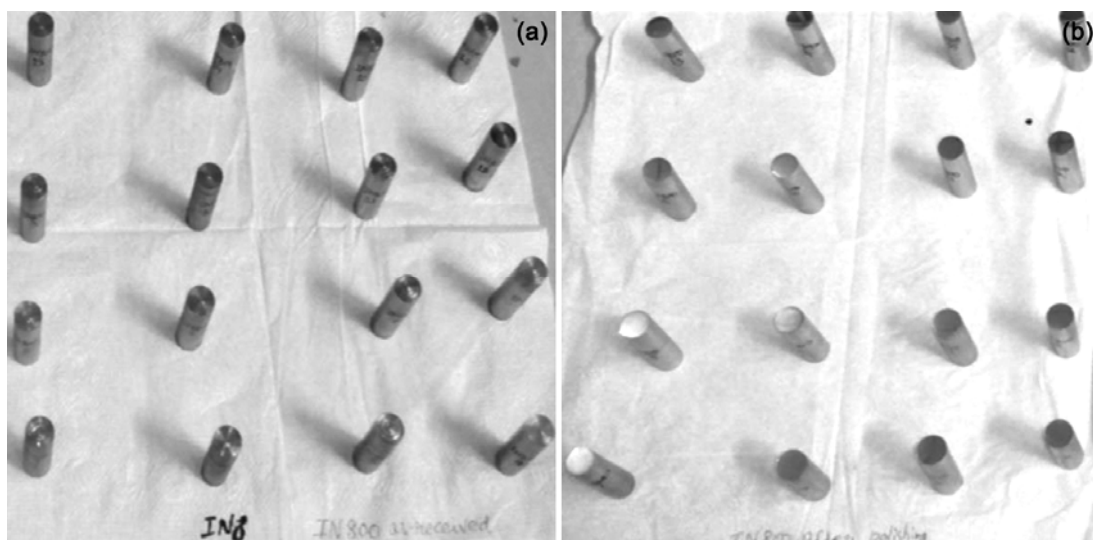


Fig. 1 — Wear samples of (a) As-received wear samples and (b) Polished IN800 wear samples.

2.2 Preparation of Samples for Sliding Wear Rate of Sol-Gel Coated IN800 Substrate (SW-NC1)

Thermal barrier coating was fabricated on the flat surface of the cylindrical pin of IN800 superalloy. The diameter and length of the pin was 10mm and 30 mm, respectively. Bond-coat of CoNiCrAlY intermetallic was applied on the flat surface by air plasma spraying²⁴. For making top-coat of 7YSZ sol-gel, sol-gel process was optimized and two routes were identified. The 7YSZ sol-gel obtained by route-II was fabricated on the bond coated flat surface by dip-coating method.

The air plasma sprayed bond coated samples before sol-gel deposition are shown in Fig. 2. For top-coat, 7YSZ sol-gel was synthesized and deposited on the bond coated substrate by automatic dip coatings machine (M/s Apex Instrument, Kolkata, India, Model: dipSV1). Dip coated IN800 SGTBC substrates were dried first at 750 °C temperature followed by drying at 800, 850, 900 and 950 °C for 8 hours to increase the strength of coating and reduce the roughness. Thereafter, sol-gel deposited top-coat super alloy substrates were aged for 24 hours at 60 °C before wear testing. The coatings obtained were smooth with roughness around Ra 3-4 μm . Finally, samples were dried and weighed using an electronic balance (Make: CONTECH, 224D) of resolution 0.01 mg¹⁵. These samples for sliding wear tests will be called SW-NC1.

2.3 Taguchi Design of Experiments

Present study is focused to selection of optimal sliding wear parameters for obtaining minimum



Fig. 2 — As- air plasma sprayed bond coated samples before sol-gel deposition.

sliding wear in uncoated (SW-B1) and coated (SW-NC1) samples. To achieve this, conventional methods require large number of experiments. Taguchi²²⁻²⁶ proposed different orthogonal arrays (OA) to reduce number of experiments and is applied in the present study. The Taguchi based design of experiment starts from the plan of a suitable orthogonal array (OA) which depends on the control factors, their levels and interactions between them. Experiments were conducted on the basis of selected orthogonal array and experimental data were examined on the basis of signal-to-noise ratio (SNR)¹⁹⁻²¹.

In the present study, dry sliding wear rate was selected as the quality characteristic for both uncoated (SW-B1) and coated IN800 substrates (SW-NC1). This quality characteristic was considered with the conception of 'smaller-the-better' for getting the

minimum possible value of wear rate⁴. Four control factors namely temperature, disc speed, load and sliding velocity were selected. These control factors are parameters which mainly affect the objective function as minimum possible value of sliding wear rate⁴. Four levels of each control factors were selected for conducting experiments and are given in Table 1.

In this methodology, the optimal levels of the sliding test conditions are the levels with the highest signal-to-noise ratio (SNR). Further, a statistical analysis of variance (ANOVA) was performed to check the statistically significant sliding wear conditions. The optimal combination of the sliding wear conditions were obtained from SNR and ANOVA analysis. In this experimental study, a L_{16} orthogonal array (OA) was selected as there were four control factors with four levels and is summarized in Table 2. Pin-On-Disc sliding wear tests were conducted as per the levels of control factors given in Table 2 for both uncoated Inconel 800 (SW-B1) superalloy and sol-gel top coated IN800 substrates (SW-NC1). After conducting tests, SNR for both coated and uncoated samples were calculated on the

Table 1 — Control factors for sliding wear and their levels.

Codes	Control factors	Levels			
		L ₁	L ₂	L ₃	L ₄
A	Temperature (°C)	25	150	275	400
B	Disc speed (rpm)	200	400	600	800
C	Normal load (N)	15	30	45	60
D	Sliding velocity (m/sec)	0.5	0.6	0.7	0.8

basis of the Eq. (1) which is used for the cases of smaller-the-better type of quality characteristic/objective function²¹⁻²⁶

$$S/R = -10 \log \left[\left(\frac{1}{n} \right) \sum (y_i^2) \right] \quad \dots (1)$$

where, n is the number of observations (test runs); y_i is the observed data for i^{th} test run. The calculated SNR combined with ANOVA were used for analysis of the experimental results and selection of optimal level of sliding wear testing conditions. These optimal conditions were confirmed by a confirmation experiment also. Analysis of influence of each sliding wear parameter was carried out by using statistical tool box MINITAB 16.0.

2.4 Dry-Sliding Wear (DSW) Test

Dry sliding wear tests were performed on both uncoated (SW-B1) and coated specimens (SW-NC1) against air plasma sprayed tungsten carbide disc using Pin-On-Disc wear testing machine as per the ASTM wear testing standard G99-95a²¹. Schematic diagram of Pin-On-Disc test rig is shown in Fig. 3. The plasma sprayed bond coating of CoNiCrAlY was prepared on one of the flat ends of the cylindrical pins, which were dip-coated by 7YSZ sol-gel coatings. For the case of uncoated SW-B1 samples, flat surface of the pin was in contact with the disc. Whereas, for coated SW-NC1 samples, coated flat surface of the cylindrical pin was in contact with the rotating disc. The coated flat

Table 2 — Experimental design matrix using L_{16} orthogonal array.

Test run	Levels				Sliding Wear Rate ($\times 10^{-6}$ g/Nm)		Smaller-the-better S/N ratios (SNR)	
	A	B	C	D	SW-B1	SW-NC1	SW-B1	SW-NC1
1	25	200	15	0.5	0.9511	0.7688	0.4354	2.283
2	25	400	30	0.6	31.542	12.909	-29.976	-22.218
3	25	600	45	0.7	26.824	12.999	-28.571	-22.278
4	25	800	60	0.8	17.734	16.489	-24.976	-24.344
5	150	200	30	0.7	0.8635	0.1597	1.275	15.933
6	150	400	15	0.8	0.3111	0.1492	10.142	16.524
7	150	600	60	0.5	2.366	0.3038	-7.480	10.346
8	150	800	45	0.6	0.8512	0.1951	1.399	14.196
9	275	200	45	0.8	0.3537	0.4694	9.027	6.568
10	275	400	60	0.7	1.288	0.4866	-2.198	6.256
11	275	600	15	0.6	0.2482	0.2074	12.106	13.663
12	275	800	30	0.5	0.8400	0.2148	1.514	13.357
13	400	200	60	0.6	1.8047	1.6302	-5.128	-4.245
14	400	400	45	0.5	1.6793	1.1466	-4.502	-1.188
15	400	600	30	0.8	1.1931	0.9144	-1.533	0.777
16	400	800	15	0.7	0.8104	0.7479	1.825	2.523
	Average of SNR, \bar{T}						-1.043	1.759

surface of the cylindrical pin with contact of rotating disc is shown in Fig. 4. For both the cases, disc was air plasma sprayed tungsten carbide disc^{15,27}. The high temperature tests were performed with a chamber heating arrangement of the test rig. Room temperature pin-on-disc test set-up and chamber heating arrangement test set-up are shown in Fig. 5 (a & b). The micro-hardness of the uncoated IN800 pin, sol-gel 7YSZ coated pin and air plasma sprayed tungsten carbide rotating disc was 645 HV_{0.01}, 856 HV_{0.01} and 1895 HV_{0.01} respectively. The micro-hardness measurement was performed using a fully automatic Vickers micro-hardness tester (Make: Walter UHL, Germany. Model: VMHT 001). A load of 10 gram

force (0.098 Newton) for 15 second was applied to evaluate the hardness. Hardness was measured at 10 random locations and average value was selected. Wear tests were performed as per the levels of four control factors given in Table 1 and Table 2. Sixteen experiments for both the cases were conducted, as per L₁₆ orthogonal array as given in Table 2. Maximum test duration of 20 minutes was used to evaluate the sliding wear properties of the coatings. For uncoated samples, after every 10 minutes of test run, weight of the sample was measured and the wear debris were removed to avoid the presence of any wear debris between the contacting surfaces. The worn uncoated test sample, after each test interval, was cleaned in

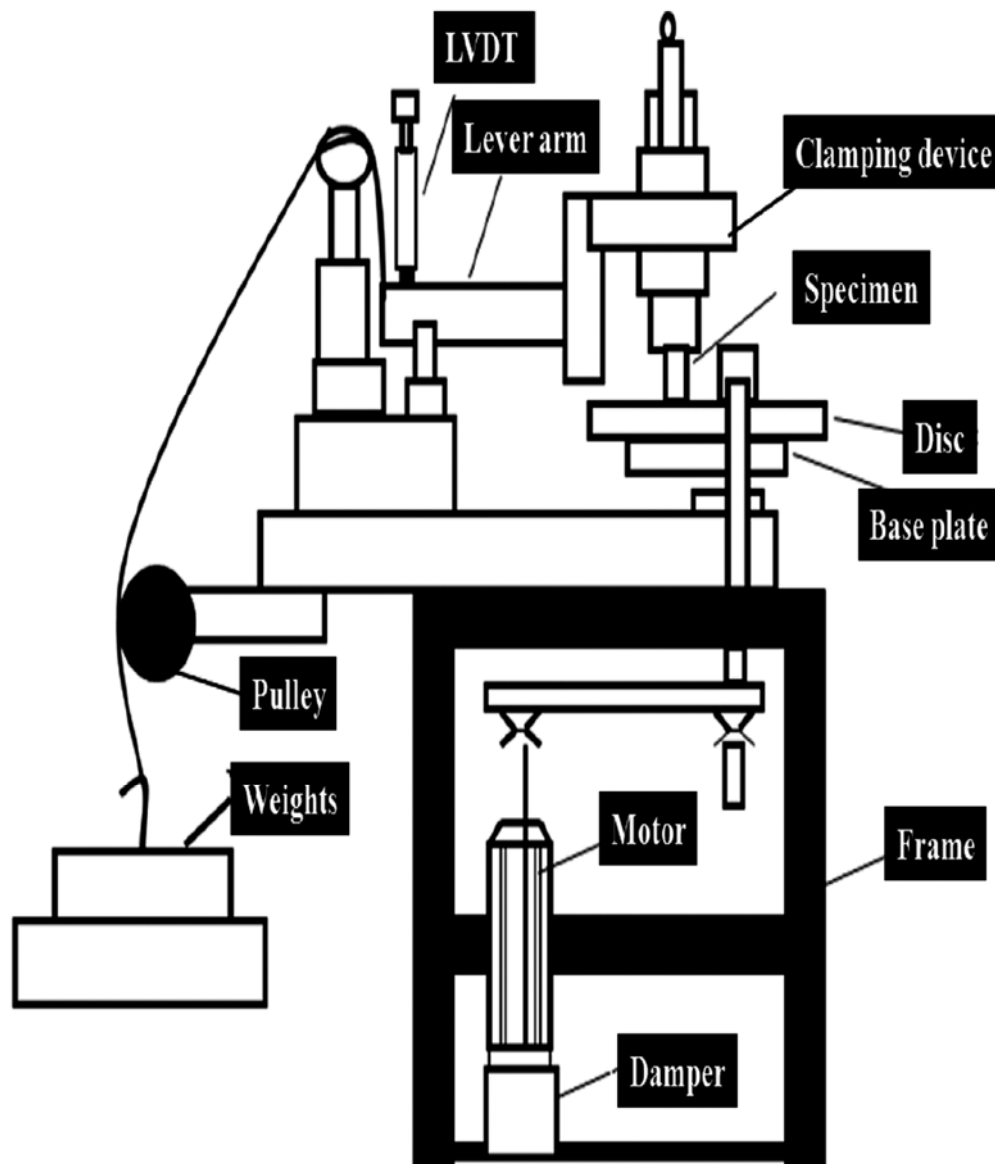


Fig. 3 — The schematic view of the pin on disc apparatus used in this study.

acetone, dried and re-weighed to get the weight loss. In the case of sol-gel TBC samples, after each test interval, samples were cleaned off from loose debris using compressed air and re-weighed. The process continues till total penetration of the coating occurred. The wear testing was carried out thrice to ensure the repeatability of the test and an average value was selected. The wear rate (g/Nm) was calculated as the ratio of wear weight loss in gram divided by the applied load and sliding distance¹⁶. The results of sliding wear rate for both uncoated (SW-B1) and coated (SW-NC1) samples are given in Table 2.

Weight loss of both coated and uncoated samples during the wear test was measured using an electronic balance with a resolution of $\pm 0.01\text{mg}$ ¹⁵. Wear tested uncoated IN800 superalloy samples (SW-B1) and sol-gel coated IN800 superalloy substrates (SW-NC1) are shown in Fig. 6 and Fig. 7, respectively.

3 Results and Discussion

3.1 Analysis of Effect of Control Factors on Sliding Wear

The sixteen experimental test runs conducted as per Table 2 are summarized in Fig. 8 for uncoated IN800

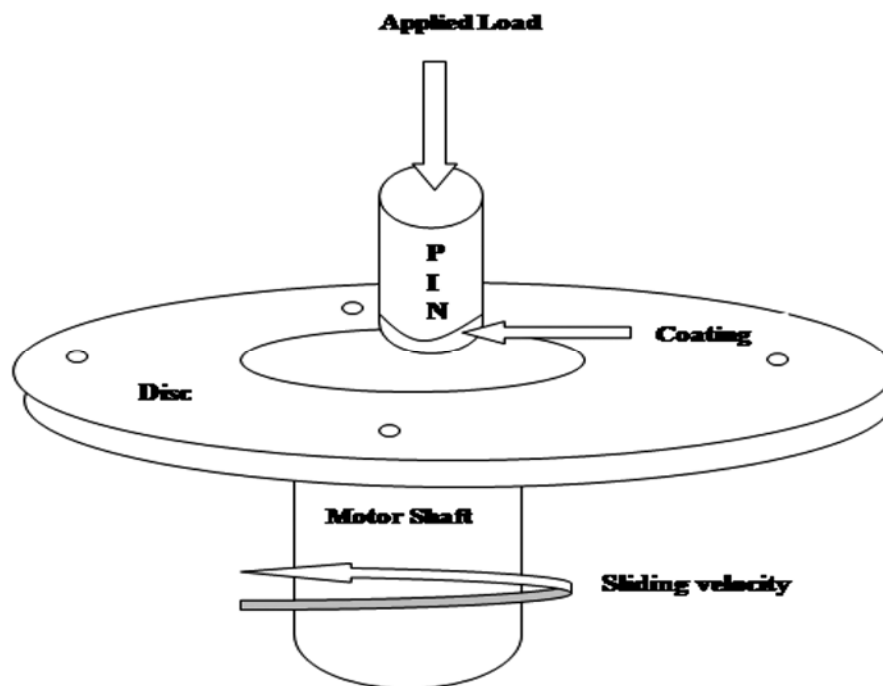


Fig. 4 — Friction and wear tester with pin-on-disc configuration.



Fig. 5 (a) — Pin-on-disc test set-up.

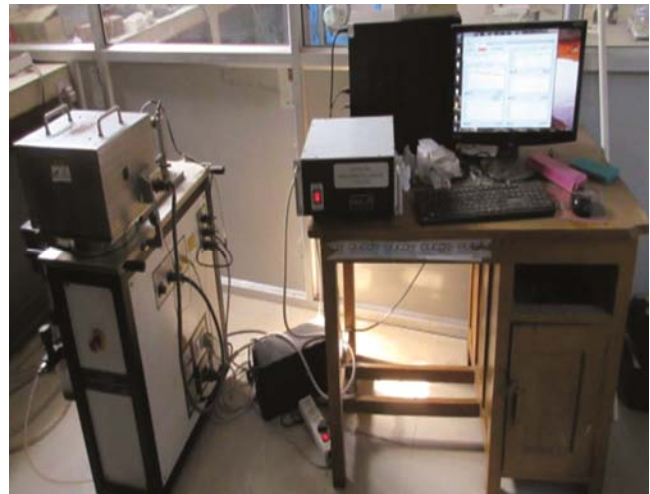


Fig. 5 (b) — Pin-on-disc test set-up with chamber heating.



Fig. 6 — Worn surface of uncoated IN800 substrate.



Fig. 7 — Worn surface of coated IN800 SGTBC.

superalloy and 7YSZ sol-gel coated IN800 superalloy substrate. Wear characteristics of the uncoated and coated substrate was measured in terms of comparative wear rate. The plotted points are average value of wear rate as per Table 2. From the Fig. 8, it was found that the sliding wear rate of uncoated superalloy is more than coated samples before damage. For the case of uncoated samples, sliding wear is maximum under test run conditions of 2 where temperature was 25 °C, disc speed was 400 rpm, sliding velocity was 0.6 m/sec and applied load was 30 N (Fig. 8). With the increase in temperature wear rate decreases for fixed load conditions. Steep drop of wear rate was observed between room temperature and 150 °C. With further

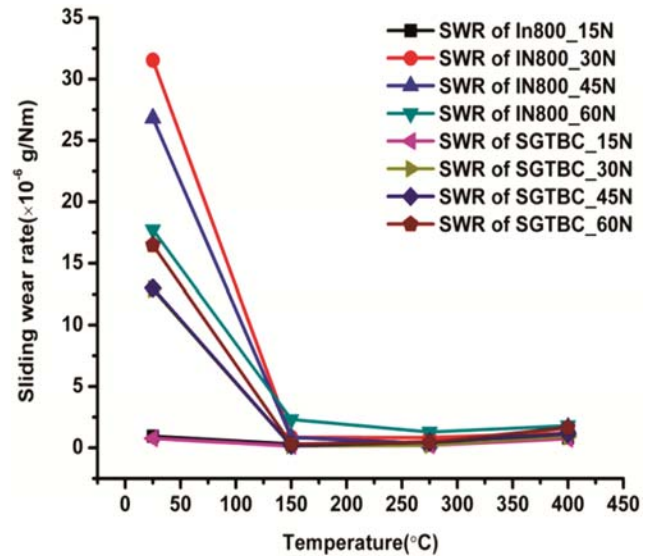


Fig. 8 — Effect of temperature on wear rate of uncoated IN800 and coated SGTBC substrate.

increase in temperature there was slight increase in wear rate for most of the test run conditions. For uncoated IN800 samples, highest wear rate (31.542×10^{-6} g/Nm) was observed at room temperature and applied load of 30 N, disc speed of 400 rpm, 0.6 m/sec of sliding velocity (Test run 2). At room temperature for uncoated alloy, minimum wear rate (0.9511×10^{-6} g/Nm) is for test run 1 with 15 N applied load, 200 rpm of disc speed and 0.5 m/sec of sliding velocity. However, for coated alloy at room temperature, maximum (16.489×10^{-6} g/Nm) and minimum (0.7688×10^{-6} g/Nm) wear rate are for test run 4 for 60 N applied load, 800 rpm of disc speed, 0.8 m/sec of sliding velocity and test run 1 for 15 N of applied load, 200 rpm of disc speed, 0.5 m/sec of sliding velocity, respectively. Whereas, for coated samples at high temperature of 400 °C, wear rate is almost constant for all operating conditions. Under similar condition, the wear rate of uncoated samples are slightly more than the coated ones. The high wear resistance of the sol-gel derived coating compared to base metal is attributed to high hardness, low thermal conductivity, high phase stability and formation of oxides of coating materials at high applied load, disc speed and sliding velocity²⁷⁻³⁰.

3.2 Optimization of Control Factors for Wear Rate

From the experimental results studied in previous section, it was observed that clear behavior of wear rate of uncoated and YSZ sol-gel coated samples of IN800 samples can not be predicted by varying one

parameter at a time. To better understand the effect of experimental parameters (i.e. control factors) such as effect of temperature, disc speed, load and sliding velocity on wear rate behavior of uncoated IN800 superalloy (SW-B1) and 7YSZ sol-gel top-coated IN800 superalloy substrate (SW-NC1), optimization analysis of the control factors was conducted.

Results of the sliding wear experiments conducted as per L_{16} orthogonal array of Taguchi are given in Table 2 for both uncoated IN800 superalloy substrate and 7YSZ sol-gel coated TBC. Signal-to-Noise Ratio (SNR) was calculated as per the expression for “the-smaller-the-better” type of optimization as expressed by Eq. (1). SNR for uncoated and coated samples are also given in Table 2. The average SNR for each control factor at each level is given in Table 3a for uncoated IN800 and in Table 3b for 7YSZ sol-gel coated IN800 samples (SW-NC1). In Table 3a and 3b, Δ_{factor} is the difference between largest and smallest average SNR for a particular control factor. From this difference, percentage contribution which is a ratio of Δ_{factor} and summation of Δ_{factor} of all control

factors is calculated. For the case of uncoated samples (Table 3a), the percentage contribution ratio is maximum for temperature. Therefore, the most influencing factor for minimization of wear rate for uncoated samples is temperature, followed by load, disc speed and sliding velocity. For the case of 7YSZ, sol-gel coating, the most influencing factor for minimization of wear rate is again temperature followed by load, sliding speed and disc speed. The average of SNR for each level of control factors is shown in Fig. 9a and 9b.

From Fig. 9 (a & b), temperature is the dominant performance characteristics among all other factors for both uncoated IN800 superalloy and 7YSZ sol-gel coated superalloy. Better performance is obtained at A_3 level of temperature and thus the lowest wear rate for uncoated superalloy is at 275°C temperature. The temperature sensitivity of IN800 superalloy increases hardness resulting in low wear rate at 275°C but wear rate increases with further increase of temperature. In Fig. 9b, highest performance characteristic is achieved at 150°C by the application of YSZ sol-gel coating. At all tested temperature, wear rate of the

Table 3a — Average SNR for sliding wear rate (SWR) of IN800 substrate.

Level	Control factors			
	Temperature(°C)	Disc speed(rpm)	Load(N)	Sliding velocity(m/sec)
1	$A_1 = -20.772$	$B_1 = 1.4022$	$C_1 = 6.127$	$D_1 = -2.5082$
2	$A_2 = 1.1334$	$B_2 = -6.6339$	$C_2 = -7.1800$	$D_2 = -5.3997$
3	$A_3 = 5.1123$	$B_3 = -6.3695$	$C_3 = -5.6618$	$D_3 = -6.9173$
4	$A_4 = -2.3340$	$B_4 = -5.0595$	$C_4 = -9.945$	$D_4 = -1.835$
Δ_{factor} = Difference of maximum and minimum Contribution ratios (%) = $\frac{\Delta_{factor}}{\Delta_{total}}$	25.884	7.772	16.072	5.082;
	47.22	14.17	29.32	$\Delta_{total} = 54.81$ 9.27
Rank	1	3	2	4

Table 3b — Average SNR for sliding wear rate of SGIN800W.

Level	Control factors			
	Temperature(°C)	Disc speed(rpm)	Load(N)	Sliding velocity(m/sec)
1	$A_1 = -16.639$	$B_1 = 5.1347$	$C_1 = 8.7483$	$D_1 = 6.1995$
2	$A_2 = 14.2490$	$B_2 = -0.1565$	$C_2 = 1.9623$	$D_2 = 0.3492$
3	$A_3 = 9.961$	$B_3 = 0.6270$	$C_3 = -0.6754$	$D_3 = 0.6085$
4	$A_4 = -0.5333$	$B_4 = 1.4332$	$C_4 = -2.9967$	$D_4 = -0.1187$
Δ_{factor} = Difference of maximum and minimum Contribution Ratios (%) = $\frac{\Delta_{factor}}{\Delta_{total}}$	30.888	5.2912	11.745	6.3182;
	56.94	9.75	21.65	$\Delta_{total} = 31.769$ 11.65
Rank	1	4	2	3

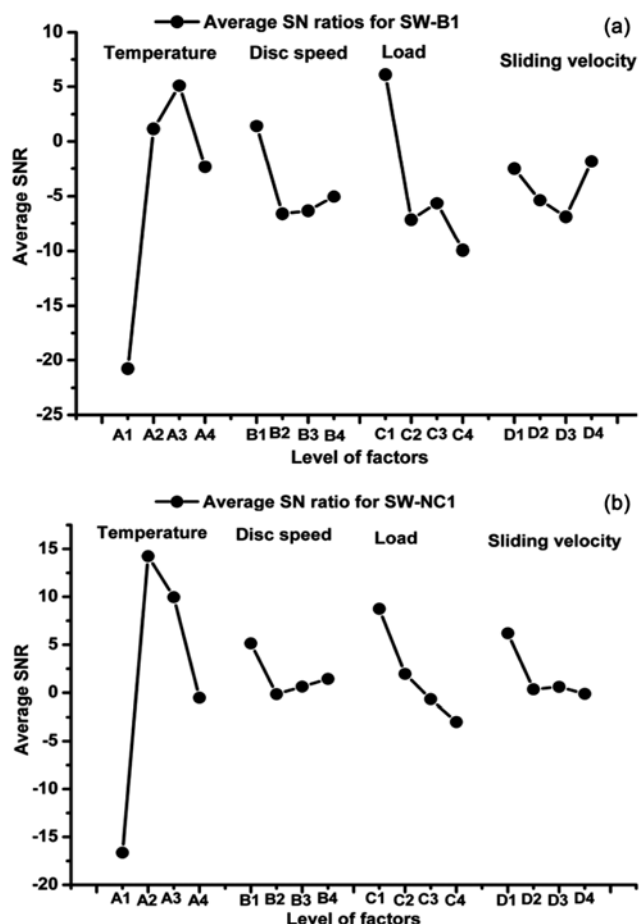


Fig. 9 — The effect of control factors A, B, C and D on sliding wear behavior.

nanostructured sol-gel coating is less as compared to the uncoated metallic substrate IN800. A small amount of friction heat generated due to sliding action during wear test is transmitted to the 7YSZ coating layer because of the low thermal conductivity of 7YSZ coating materials. This may be the reason of formation of hard ceramic oxide in the contact region. The wear rate of uncoated and coated samples was more at room temperature than high temperature tests. This is due to generation of high frictional heat below the small surface area of the pin as compared to the disc. Possibility of grain growth and densification of nanostructured 7YSZ coating at high temperature improves the wear resistance¹⁸. Yield strength of tungsten carbide (WC) disc is high at room temperature and decreases with increase in temperature¹⁸. With increase in temperature, fine-grains of carbide become coarser, slightly increasing the ductility¹⁸. Lowest wear resistance (negative values of wear rate) of uncoated IN800 pin samples

and coated samples at high temperature is mainly due to very high yield strength and creep resistance of tungsten carbide coated disc. Due to high frictional heating and testing temperature, the wear resistance of as-air plasma sprayed tungsten carbide coated disc recrystallizes more easily depending on mating body in contact during wear test^{27,28}. Therefore, the wear resistance decrease monotonically after 275 °C for uncoated superalloy and after 150 °C for coated pins.

First level of parameter B (i.e. B₁) is having highest average SNR for both uncoated and coated samples as shown in Fig. 9a and Fig. 9b, respectively. Therefore, wear rate is minimum at this level of disc speed for both coated and uncoated samples. For both uncoated and coated samples, lowest average SNR is for 400 rpm disc speed (i.e. B₂) indicating high wear rate at this level of disc speed for both the cases. With increase in disc speed, the wear rate increases irrespective of the contact material surface under sliding conditions. With a further increase in disc speed (400 rpm), more contact area of the pin sample comes in contact with the hard disc. During the increase of contact area between pin sample and disc, more thermal stress and tangential impact effect are developed inside the asperities²⁸. The impact stress inside the asperity fractures is in a brittle manner. During very high disc speed of 600 rpm and 800 rpm, a high frictional heat is produced between the uncoated pin surface and tungsten carbide coated counter hard disc. Due to high frictional heat, a plastic flow stress develops inside the asperities resulting in elastic wear²⁷. This is the reason of low wear rate of uncoated pin sample at 600 rpm and 800 rpm compared to 400 rpm disc speed (Fig. 9a). At high disc speed of 600 rpm and 800 rpm, low wear rate is also observed for sol-gel coated pin samples but the wear mechanism of 7YSZ sol-gel coated pin sample is different from the base metal. High rotational disc speed produces high frictional heat, but as the 7YSZ ceramic coatings has very low thermal conductivity, a sharp thermal gradient develops between coated pin sample and coated counter tungsten carbide disc and accordingly the thermal stresses are developed in the surface layer of the coating^{27,28}. In contrary, for the case of sol-gel coating, that amount of thermal gradient will not develop and the high disc speed will smoothen the coating layers under high temperature. The material degrades under this condition with polishing abrasion mechanisms. This is the reason of low wear rate at 600 rpm and 800 rpm of disc speed as compared to 400 rpm disc speed (Fig. 9b).

For control parameter C (*i.e.* applied load) high average SNR is for first level of parameter C (*i.e.* applied load of 15N). Therefore, wear rate will be minimum at this level of parameter C for the case of both uncoated and coated IN800 substrates. Although, parameter C was observed to be only significant control factor for wear of uncoated samples. It was observed that, regardless of the magnitude of the applied load, the uncoated substrate has a much higher wear rate than the coated substrates. For each case whether coated or uncoated, the wear rate, in general, increases with the increase in applied load as expected. Increase of wear rate, with increase of load, is mainly due to increase of shear load and elastic or plastic deformation state below the surface of pin sample due to more area of contact with load. The developed shear stress between the hard asperities of tungsten carbide counter surface disk and hard surface of superalloy in contact may be the reason of increased wear resistance¹⁵. In the case of both uncoated and coated materials under low load conditions of 15N, high performance characteristics and thus low wear rate was observed. It means low quantity of asperities is there at the area of contact and hence tungsten carbide hard disc is in elastic contact with the pin samples. Obviously, less material removal is taking place under 15-30 N. Further some less wear rate or high-performance characteristics was observed at 45 N in the case of base material, showing a combined action of polishing and abrasion rather than only material removal¹⁵. Linearly increase of wear rate or decrease in performance characteristics of sol-gel coated samples against tungsten carbide hard disc is attributed to the abrasive action of detached coating particles which were entrapped in the contact area of the disc. The polishing abrasion produces fine particles of nano coating material between the ceramic coating and the tungsten carbide disc. These fine particles act as a bearing agent which can not only bear the applied load but also prevent direct contact, resulting in decrease of wear rate¹⁴. In the case of base metal under very high loads, the gross removal of plasticized surface takes place leading to the formation of substantially large-sized wear debris. In the case of coated samples, comparatively less wear rate or high performance characteristics is due to the granular debris coming out from the adhesion-induced spallation of the coating material.

Similarly, fourth level of parameter D (*i.e.* sliding velocity), shows the higher performance

characteristics (Fig. 9a) indicating low wear rate in the uncoated superalloy substrate. For the case of 7YSZ sol-gel coating, the first level of parameter D (*i.e.* sliding velocity of 0.5 m/sec) is having the highest performance characteristics and thus lowest wear rate. From the current dry sliding wear tests, it was also realized that the wear rate of base metal is low at the high sliding velocity (0.8 m/sec) as compared to the low sliding velocity (0.6 m/sec, 0.7 m/sec)(Fig. 9a). Although, at very low sliding velocity of 0.5 m/sec, wear rate of base metal against tungsten carbide coated disc was found to be very low, which was little high at 0.8 m/sec of sliding velocity. For sol-gel non conventional (NC) coating, worn surface appears to be smooth under the influence of high sliding velocity and high temperature conditions. The obtained behavior of worn surface is due to the thermo-mechanical aging treatment^{15,31-32}. It produces large difference of thermal expansion coefficient between sol-gel nanostructured coated pin samples and counter tungsten carbide coated disc. As tungsten carbide disc is very hard so it easily produces residual stresses on sol-gel coated pin samples and may suppress path of cracks propagation and delamination of coatings as well¹⁴. This was the reason of better performance characteristic observed at first level of sliding velocity (Fig. 9b).

It was observed that in order to obtain minimum wear rate in uncoated IN800 superalloy substrate, the optimum level of parameters were temperature A₃ (275 °C), the disc speed B₁ (200 rpm), load C₁ (15N) and the sliding velocity D₄ (0.8 m/sec). For the case of SG coated 7YSZ ceramics IN800 substrate (SW-NC1), the optimum level of parameters were temperature A₂ (150 °C), the disc speed B₁ (200rpm), the applied load C₁ (15N) and the sliding velocity D₁ (0.5 m/sec). These values are summarized in Table 4

Table 4 — Optimum control factors of low sliding wear rate in SW-B1 and SW-NC1 samples.

	Control factors			
	Temperature (°C)	Disc speed (rpm)	Load (N)	Sliding velocity (m/sec)
IN800 substrate (SW-B1)				
Optimum level	A ₃	B ₁	C ₁	D ₄
Optimum value	275	200	15	0.8
IN800SGTBC (SW-NC1)				
Optimum level	A ₂	B ₁	C ₁	D ₁
Optimum value	150°C	200	15	0.5

also. It is seen that the presence of a sol-gel 7YSZ coating significantly reduces the wear rate in comparison to uncoated metallic alloy substrate.

In order to obtain the influence of the each parameter on wear rate on uncoated IN800 superalloy and SG coated IN800 superalloy substrates analysis of variance (ANOVA) was also applied. The results of ANOVA for uncoated superalloy and SG coated 7YSZ ceramics superalloy are presented in Table 5a and 5b, respectively using the statistical tool MINITAB 16.

The percentage contribution ratio of each control factor for uncoated IN800 superalloy substrate for 7YSZ sol-gel coating is shown in Table 3a (Fig. 10a) and Table 3b (Fig. 10b), respectively. Significance parameter for both the cases are also shown in Fig. 11 which is based on the average SNR for each control factors (Table 2).

4 Confirmation Experiment

The validation of optimized control factors (Table 4) was carried out by conducting confirmation tests. The confirmation tests were performed on two sets of control factors namely $A_3B_1C_1D_4$ and $A_2B_1C_1D_1$ obtained from optimization analysis for uncoated superalloy IN800 substrate (SW-B1) and SG coated 7YSZ IN800 (SW-NC1) substrate, respectively. From confirmation tests, the wear rate at optimum control factors of $A_3B_1C_1D_4$ for uncoated IN800 substrate was obtained as $0.2236 (\times 10^{-6} \text{g/Nm})$ which is low among the all wear rates observed for all test runs (Table 2). The SNR at this level of control factor was 13.011 dB

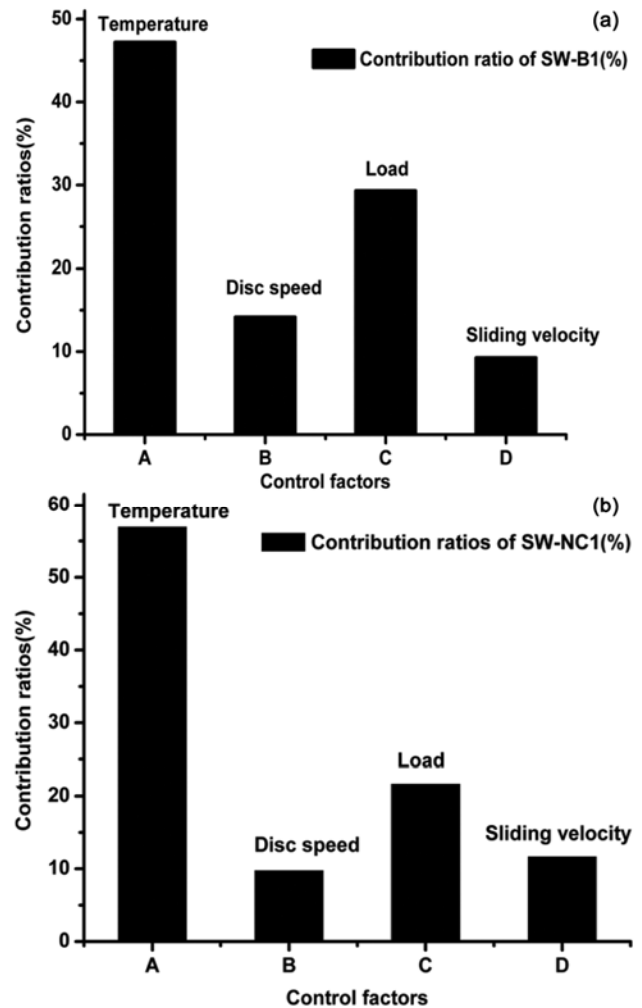


Fig. 10 — The contribution ratio of each control factors: (a) Uncoated IN800 superalloy and (b) Coated IN800SGTBC.

Table 5a — Analysis of variance (ANOVA) of S/N ratios for sliding wear rate of SW-B1 samples.

Factors	DOF	Sum of square	Variance	F-ratio	Percentage contribution	P-value	Importance
A (Temperature)	3	1581.78	527.26	18.28	65.24	0.020	Most Significant
B (Disc speed)	3	170.99	57.00	1.98	7.06	0.295	Not significant
C (Load)	3	602.69	200.90	6.96	24.84	0.073	Slightly significant
D (Sliding velocity)	3	69.09	23.03	0.80	2.86	0.571	Not significant
Error	3	86.53	28.84				
Total	15	2511.09		28.02			

Table 5b — Analysis of variance (ANOVA) of S/N ratios for sliding wear rate of SW-NC1 samples.

Factors	DOF	Sum of square	Variance	F-ratio	Percentage contribution	P-value	Importance
A (Temperature)	3	2268.17	756.06	23.25	82.48	0.014	Most Significant
B (Disc speed)	3	65.81	21.94	0.67	2.38	0.623	Not significant
C (Load)	3	309.74	103.25	3.18	11.28	0.184	Not significant
D (Sliding velocity)	3	106.22	35.41	1.09	3.86	0.473	Not significant
Error	3	97.55	32.52				
Total	15	2847.49		28.19			

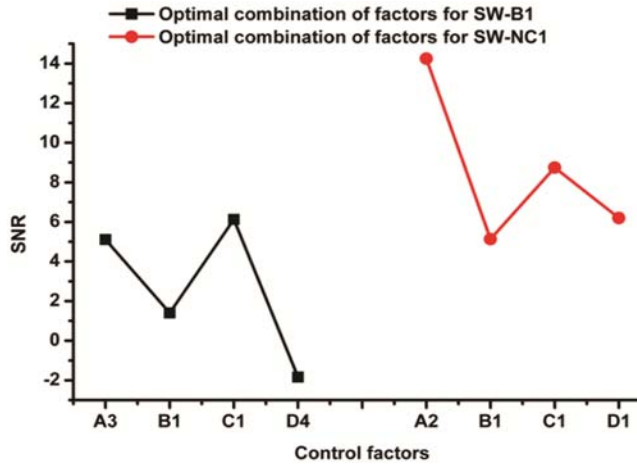


Fig.11 — Optimal combinations of control factors for uncoated IN800 and coated IN800 SGTBC.

and improvement with respect to $A_3B_3C_1D_2$ levels of control factors (test run 11 of Table 2) was 12.106 dB (Table 6). Similarly, confirmation test was conducted at optimum control factors of $A_2B_1C_1D_1$ for 7YSZ sol-gel coating. Sliding wear rate at this level of experimental parameters was $0.12536 (\times 10^{-6} \text{ g/Nm})$ (Table 7). Level $A_2B_2C_1D_4$ is corresponding to minimum wear obtained for the case of sol-gel coated samples for test run 6 of Table 2. Therefore, wear rate obtained at optimal parameters is minimum among all test results shown in Table 2 for coated sample also. The SNR was 18.036 dB (Table 6) which was also more than the presented SNR in Table 2 and comparative SNR values are also clear from Fig. 11. Improvement in SNR, see in Fig. 11, with respect to optimized control factors $A_3B_1C_1D_1$ and SNR corresponding to $A_2B_2C_1D_4$ (test run 6, Table 2) is 1.512 dB for coated sample (Table 6). The SNR for optimum control parameters $A_3B_1C_1D_4$ can also be predicted for sliding wear rate in uncoated IN800 superalloy substrate (SW-B1), $(\eta_{IN800})_{SW}$ with the help of Eq. (2)⁴:

$$(\eta_{IN800})_{SW} = \bar{T} + \left(\bar{A}_3 - \bar{T} \right) + \left(\bar{B}_1 - \bar{T} \right) + \left(\bar{C}_1 - \bar{T} \right) + \left(\bar{D}_4 - \bar{T} \right) \quad \dots (2)$$

where, \bar{T} is the average of SNR values (-1.043 dB)

as given in Table 2 and $\bar{A}_3, \bar{B}_1, \bar{C}_1, \bar{D}_4$ are average SNR at control factors A_3, B_1, C_1 and D_4 as given in Table 3a. Similarly, the SNR for sliding wear rate in IN800 SGTBC corresponding to optimum control

Table 6 — Results of the confirmation experiments for sliding wear rate in IN800.

Level	Initial Parameters $A_3B_3C_1D_2$ (As per test run 11 of Table 2)	Optimum Parameters	
		$A_3B_1C_1D_4$ (Calculated as per Equation 2)	$A_3B_1C_1D_4$ (Experimental)
Sliding wear rate (g/Nm)	0.24815×10^{-6}	-----	0.2236×10^{-6}
SNR (dB)	12.106 dB	13.935 dB	13.011 dB
Improvement of S-N ratio for sliding wear rate = $13.011 - 12.106 = 0.905 \text{ dB}$			

Table 7 — Results of the confirmation experiments for sliding wear rate in SGIN800W.

Level	Initial Parameters $A_2B_2C_1D_4$ (As per test run 6 of Table 2)	Optimum Parameters	
		$A_2B_1C_1D_1$ (Calculated as per Equation 3)	$A_2B_1C_1D_1$ (Experimental)
Sliding Wear Rate (g/Nm)	$0.1492 (\times 10^{-6})$	-----	$0.12536 (\times 10^{-6})$
SNR (dB)	16.524	32.572	18.036
Improvement of S-N ratio for sliding wear rate = $18.036 - 16.524 \text{ dB} = 1.512 \text{ dB}$			

factors $A_2B_1C_1D_1$ can be calculated by the following predictive Eq. (3)⁴

$$(\eta_{SGTBC})_{SW} = \bar{T} + \left(\bar{A}_2 - \bar{T} \right) + \left(\bar{B}_1 - \bar{T} \right) + \left(\bar{C}_1 - \bar{T} \right) + \left(\bar{D}_1 - \bar{T} \right) \quad \dots (3)$$

where, $(\eta_{SGTBC})_{SW}$ is the SNR for optimum level of control factors $A_2B_1C_1D_1$ for SW-NC1 sample, \bar{T} is the average of SNR for coated samples (1.759 dB)

as given in Table 2 and $\bar{A}_2, \bar{B}_1, \bar{C}_1$ and \bar{D}_1 are average SNR at these levels of control factors as given in Table 3b. The predicted SNR are given in Table 6 and Table 7 for uncoated and coated samples respectively. The predicted SNR was found to be 13.935 dB for uncoated sample and 32.572 dB for coated sample.

5 Conclusions

In the present Pin-On-Disc dry sliding wear investigation, the effect of wear parameters namely the temperature, applied load on the pin, disc speed of the counter-body and sliding velocity were studied

using L_{16} orthogonal array of Taguchi Design of Experiment. The specimen was uncoated and nanostructured 7YSZ sol-gel coated IN800 superalloys. Following conclusions were derived from the study:

- (i) Thick sol-gel derived YSZ ceramic coating was fabricated by dip coating on flat surface of the cylindrical specimen of IN800 superalloy.
- (ii) Out of the four parameters considered, the temperature was the most significant factor affecting the wear rate of the uncoated and coated samples. For the case of uncoated IN800 substrates, other factors in the order of decreasing influence were the applied load, disc speed and sliding velocity. In the case of coated samples, other factors in the decreasing order of influence were applied load followed by sliding velocity and disc speed.
- (iii) Wear resistance of sol-gel 7YSZ coated samples was found more in comparison to uncoated samples for all experimental parameters and can become an economical method to improve both thermal resistance and wear resistance of IN800 superalloy.
- (iv) The optimum control factors for low wear rate of uncoated and coated IN800 superalloy were $A_3B_1C_1D_4$ and $A_2B_1C_1D_1$ respectively.

References

- 1 Li W, Li Y, Sun C, Hu Z, Liang T & Lai, *J Alloy Comp*, 506 (2010) 77.
- 2 Guo C, Zhou J, Chen J, Zhao J, Yu Y & Zhou H, *Wear*, 270 (2011) 492.
- 3 Fernandes F, Cavaleiro A & Loureiro A, *Surf Coat Technol*, 207 (2012) 196.
- 4 Kosal S, Ficici F, Kayikci R & Savas O, *Mater Des*, 42 (2012) 124.
- 5 Gallardo J M, Rodriguez J A & Herrera E J, *Wear*, 252 (2012) 264.
- 6 Panagopoulos C N, Giannakopoulos K I & Saltas V, *Mater Lett*, 57 (2003) 4611.
- 7 Rynio C, Hattendorf H, Klower J & Eggeler G, *Wear*, 315 (2014) 1.
- 8 Rynio C, Hattendorf H, Klower J & Eggeler G, *Wear*, 317 (2014) 26.
- 9 Palavar O, Ozyurek D & Kalyon A, *Mater Des*, 82 (2015) 164.
- 10 Zois D, Lekatou A, Vardavoulis M, Panagiotopoulos I & Vazdirvanidis A, *J Therm Spray Technol*, 17 (2008) 887.
- 11 Boleli G, Bonferroni B, Cannillo V, Gadow R, Killinger A & Lusvarghi L, *Surf Coat Technol*, 204 (2010) 2657.
- 12 Gell M, Jordan E H, Sohn Y H, Goberman D, Shaw L & Xiao D, *Surf Coat Technol*, 146-147 (2001) 48.
- 13 Rico A, Rodriguez J, Otero E, Zeng P & Rainforth W M, *Wear*, 267 (2009) 1191.
- 14 Singh V P, Sil A & Jayaganthan R A, *Mater Des*, 32 (2011) 584.
- 15 Ramachandran C S, Balasubramanian V, Ananthapadmanabhan P V & Viswabaskaran V, *Mater Des*, 39 (2012) 234.
- 16 Ahn HS & Kwon OK, *Wear*, 162-164 (1993) 636.
- 17 Preece C M & Macmillan N H, *Annual Rev Mater Sc*, 7 (1977) 95.
- 18 Muratore C, Voevodin A A & Muratore C, *Annual Rev Mater Res*, 39 (2009) 297.
- 19 Aoudi S M, Luster B, Kohli P, Muratore C & Voevodin A A, *Surf Coat Technol*, 204 (2009) 962.
- 20 ASM aerospace specifications metals Inc, 800, 398-4345.
- 21 ASTM G99-5a, Standard test method for wear testing with a pin-on-disc apparatus, Pennsylvania: American Society for Testing and Materials, 2000.
- 22 Kumar D & Pandey K N, *Proc Inst Mech Eng, Part L: J Mater Des Appl*, 231 (2017) 600.
- 23 Kumar D, Pandey K N & Das D K, *Proc Inst Mech Eng, Part L J Mater Des Appl*, 232 (2018) 582.
- 24 Kumar D, Pandey K N and Das D K, *Int J Minerals, Metal Mater*, 23 (2016) 934.
- 25 Wang Q, Melaen, M C, De Silva T S & Gong G, *Powder Technol*, 160 (2005) 93.
- 26 Montgomery D C, Design and analysis of experiments, New Delhi: John Wiley & Sons Ltd., 2007, ISBN 978-1118-14692-7.
- 27 Kim H J, Kweon Y G & Chang R W, *J Therm Spray Technol*, 3 (1994) 169.
- 28 Ndlovu, S, *The wear properties of tungsten carbide cobalt hard metals from the nanoscale up to the macroscopic scale*, Ph.D. Thesis, Erlangen, 1999.
- 29 Kumar D & Pandey K N, *Int J Surf Sci Eng*, 10 (2016) 303.
- 30 Aruna S T, Balaji N & Rajam K S, *Mater Char*, 62 (2011) 697.
- 31 Tlili B, Barkaoul A & Walock M, *Trib Int*, 102 (2016) 348.
- 32 Neska-Bakus P & Piwonski I, *Tribologia*, 1 (2011) 117.